43

Research Report

Integrated Basin Modeling

Geoff Kite
and
Peter Droogers

International Water Management Institute

Research Reports

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This study was conducted as part of a collaborative research program between the General Directorate of Rural Services (GDRS) in Turkey and the International Water Management Institute (IWMI) and was funded by the Government of Turkey as part of the World Bank-assisted Turkish Agricultural Research Plan (TARP). IWMI also gratefully acknowledges the financial support for its research work from the following Governments, Development Banks, Agencies, and Foundations: Australia, Brazil, Canada, China, Denmark, France, Germany, India, Iran, Japan, Netherlands, Norway, Pakistan, South Africa, Sweden, Switzerland, Taiwan, Turkey, European Union, United Kingdom, and United States of America; African Development Bank (AfDB), Asian Development Bank (ADB), and World Bank; Agricultural Engineering Research Center (AERC), Council of Agriculture (COA), Food and Agriculture Organization of the United Nations (FAO), and International Fund for Agricultural Development (IFAD); Chi-Seng Water Management and Development Foundation, Environment Greening Foundation, Ford Foundation, Taoyan Irrigation Research and Development Foundation, and Tsao-Jiin Memorial Foundation for R&D for Agriculture and Irrigation. The Governments of India, Iran, Mexico, Nepal, Pakistan, Sri Lanka and Turkey provided program support for IWMI-related activities in these countries.

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Kite, G. and P. Droogers. 2000. *Integrated basin modeling.* Research Report 43. Colombo, Sri Lanka: International Water Management Institute.

/ water balance / irrigation management / groundwater / river basins / hydrology / flow / simulation models / evapotranspiration / precipitation / soils / Turkey / Gediz basin /

ISBN 92-9090-411-9
ISSN 1026-0862

Please direct inquiries and comments to: *iwmi-research-news@cgiar.org*

Contents

Glossary

ASA	Aggregated Simulation Area
AVHRR	Advanced Very High Resolution Radiometer
DEM	Digital Elevation Model
DMSP SSM/I	Defence Military Satellite Program, Special Sensor Microwave Instrument
E	Soil Evaporation
LAI	Leaf Area Index
LUS	Land Use System
MLB	Menemen Left Bank
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanographic and Atmospheric Administration
PW	Productivity of Water
SLURP	Semi-Distributed Land Use-Based Runoff Processes
SLURPAZ	Data conversion program from TOPAZ into SLURP
SRB	Salihli Right Bank
SWAP	Soil-Water-Atmosphere-Plant
SWE	Snow Water Equivalent
T	Crop Transpiration
TOPAZ	TOpographic PArameteriZation
USGS	United States Geological Survey

Summary

River basins are complex areas, combining the natural processes of precipitation, evapotranspiration, surface water and groundwater runoff with man-made features such as dams and reservoirs, diversions and irrigation schemes, and industrial and urban water uses. Computer models may be constructed to represent these natural and man-made processes. Such models are used to help understand processes that are difficult to measure (such as evaporation) and to study the effects of changes in land cover, water management or climate on the natural and man-made processes. Usually, these models are made at a particular scale. For example, a natural river basin or an irrigation scheme may be modeled. This approach neglects the interactions between processes at the different scales.

In this study, we combine models at three different scales; the field scale, the irrigation-scheme scale and the basin scale. The advantage of this approach is that we can obtain information at one scale and apply it at other scales. For example, the productivity of an irrigation scheme could be computed using only information about that scheme. This, however, would miss the links between the irrigation scheme and other upstream and downstream water users. By using different scales we can include these links and look at the irrigation scheme within the context of the basin.

This report describes multi-scale modeling using, as an example, the Gediz basin in western Turkey. This basin contains large reservoirs, diversions, irrigation schemes and has industrial and urban water consumptions. Three linked models were built, which enabled us to look at both water productivity at the three different scales and what the impacts of changing water availability, management practice, and climate might be on irrigation productivity and on the other water users within the basin.

Integrated Basin Modeling

Geoff Kite and Peter Droogers

Introduction

Hydrological modeling simulates the conversion of precipitation to runoff through all of the natural processes involved such as evaporation, infiltration, transpiration, percolation, surface flow, interflow and groundwater flow. At the same time, hydrological models must be able to simulate those anthropogenic activities, which affect the flow of water from source to sink such as dams, reservoirs, diversions and irrigation schemes.

Using models gives two important advantages over relying solely on collected data. First, models can be used to understand processes that are difficult to measure because of complexity or temporal and/or spatial scale. Second, models can be used to study the effects of changes in land cover, water management or climate: the impacts of alternative scenarios.

Hydrological models can be applied at many different scales, from field to basin to continent. Using more than one scale can give increased insight into the processes involved and can help clarify the effects of different management options. This research report describes the application of hydrological models at three scales (figure 1). The objective of the modeling was to simulate the performance of irrigation schemes within the context of basin water resources.

Although water management practices for irrigation schemes can be evaluated and improved by modeling only the scheme itself, looking at irrigation schemes in isolation from other water uses within a river basin may not be effective. Changes in management, infrastructure, crop patterns, fertilizer and pesticide use in irrigation schemes may affect other users in the basin. And changes in other water uses—industrial, power production, and urban water supplies—can affect the quality, quantity and timing of water available for irrigated agriculture. As demand and competition for water increase, these links become more and more important, and real increases in the productivity of water will become essential if the requirements of all users are to be met. Consequently, the models applied in this project are designed to simulate irrigation schemes as one component of the overall basin water resources.

At the smallest scale, the field, the vertical water balance Soil-Water-Atmosphere-Plant (SWAP) model was used to show the relationships between water quantity and quality, and crop yields (Van Dam et al. 1997). At the

FIGURE 1.
Three different scales of hydrological model used in the study.

intermediate or irrigation-scheme level, the SWAP integrated model was used to represent types of crop, soil types, and types of irrigation (Droogers et al. 1999). This model provides information on the effects of management changes in water distribution and allocation on the productivity of irrigation schemes. At the largest scale, the SLURP hydrological model was applied to the whole basin (Kite 1997). This model divides the water basin into many subbasins known as Aggregated Simulation Areas (ASAs). Within each ASA, the model simulates each different land use separately. The detailed information derived from each land use within each ASA is integrated and routed down through the basin by the SLURP model including the effects of regulation and diversions. This enables an evaluation of each irrigation scheme against the prevailing basin-wide water management practices and water availability. Modifications in irrigation practice and climate variability are also taken into account in the model, and the hydrologic impacts of climate change can be evaluated.

Transferring data and information between the three modeling scales and integrating the outputs of all three models allow us to see the performance of individual crops within irrigation schemes, within the context of the overall water resources of the basin.

The use of hydrological models at different scales in an integrated manner is termed here "Integrated Basin Modeling."

This report describes the integrated basin-modeling concept using the Gediz basin in western Turkey as an example. The Gediz river, around 275 km in length, drains an area of 17,220 km^2 and flows from east to west into the Aegean Sea just north of Izmir, Western Turkey. The river network is controlled by four main reservoirs and four regulators are used for irrigation diversions. River flows from the heavy winter precipitation are stored in the main Demirköprü reservoir for release over the summer irrigation period. Precipitation in the basin ranges from over 1,000 mm per year in the mountains to 500 mm per year near the Aegean coast.

Crop production within the basin includes cotton, cereals, tobacco, vegetables and fruits like olives, grapes, and melons. The total irrigated area in the basin is about 150,000 hectares. Other activities in the basin include textile factories, weaving, salt production, and leather works. Urban areas within the basin are expanding and groundwater is extracted to supply water to the city of Izmir, located just outside the basin to the south.

Public Domain Datasets

Data for this integrated approach to basin modeling can be divided into two categories: areal data and point data. Areal data include topography, land cover, leaf area index (LAI) and soil characteristics. Point data include climate, streamflow and operational rules for reservoirs, dams and regulators. Obviously, climate data are needed across the whole basin but are available only as point data. Currently, two changes in methods of data access and data collection can be observed. First, data are increasingly available from global datasets, often obviating the need for both a time-consuming measurement campaign and the, sometimes tedious, process of collecting data from local agencies. Second, more and more data are collected by remote sensing (RS) instead of conventional techniques. Figure 2 shows the position of commonly used types of data within this categorization by data source and data type

(Droogers and Kite 2000). The following sections will describe these categories in terms of data sources for the Gediz basin modeling activities.

Topographic Analyses

Topographic data are more and more available as global datasets and are increasingly measured by RS techniques such as laser-altimeters. In terms of availability at basin scale, global pubic domain availability is high. In this case, a Digital Elevation Model (DEM) from a United States Geological Survey dataset was downloaded from the Internet [1].[1] These data were used to define the basin boundaries and river networks, to subdivide the basin into subbasins known as Aggregated Simulation Areas (ASAs), and to calculate the distances traveled by water from one pixel to the nearest stream and down the stream network to the ASA outlets. These products were derived by applying the TOPAZ (TOpographic PArameteriZation) program (Garbrecht and Campbell 1997) to the USGS dataset.

FIGURE 2.
Data required for integrated basin hydrological modeling as a function of availability and method of observation.

Land Cover Classification

Land cover classification has received considerable attention during the last decade as a result of a widespread concern about environmental impacts. Developments in RS and GIS have inspired many people to produce land cover maps. Two existing public-domain land cover maps were obtained and evaluated by field visits: USGS 1-km resolution global land cover map and a land cover dataset created by the State Statistical Institute of Turkey (SSI) for the whole country. Neither of the available land cover maps was found to be suitable for use in the hydrological modeling of the basin. In the case of the USGS map, the land use categories were poorly defined resulting in mixed classes. The SSI map was not sufficiently accurate in the area of interest (Droogers, Kite, and Bastiaanssen 1998). Therefore, a new land cover map was produced for the study area, which allows a more specific definition of classes in accordance with the local situation.

The base data for the new land cover map are Normalized Difference Vegetation Index (NDVI) images from the NOAA-AVHRR satellite sensor at 1-km resolution. NOAA-AVHRR data have been demonstrated to be very suitable for identifying ecologically homogeneous land units. Images are freely distributed and can be downloaded from the Internet. The great advantage of this dataset is that radiometric calibration, atmospheric correction and geometric registration for all the images are already performed. Eight images, from February to October 1995, were used. The published NDVI images were derived using the maximum NDVI value for each successive period of 10 days. The USGS DEM discussed earlier was included in the classification to distinguish different land covers in the context of their physical settings.

[1]Digits within square brackets, [1] and [2], refer to Internet sites cited at the end of this report.

A composite image was produced using three main characteristics of the area: (i) temporal variation in NDVI during the year, (ii) spatial variation of NDVI at one particular moment, and (iii) the basin topography. Temporal variation was described using a Standardized Principal Component Analysis, which produced a set of uncorrelated component images, each expressing underlying features of the input images. The first component image describes the pattern that accounts for the greatest degree of variation among the input images. The image with the greatest spatial variation was selected by visual comparison of the eight NDVI images. Values of NDVI in August appeared to give the most spatial variation, which fact agrees with our expectations considering the large differences between crops in irrigated and nonirrigated areas in that month. Finally, the physical settings of a particular area were defined by elevation using the DEM as described before.

The composite image derived was used for unsupervised classification with the CLUSTER module from IDRISI, which uses a multidimensional histogram peak cluster analysis technique (Eastman 1997). After examining several types of contrast stretches and numbers of clusters, a simple linear stretch with seven clusters gave satisfactory results. An unsupervised classification uncovers major land cover classes, without prior knowledge of what they might be. It is, therefore, necessary to define what each land cover class represents. A combination of field visits, common area knowledge and information from topographic maps was used to define each land cover class.

Leaf Area Index

As shown in figure 2, datasets for leaf area index (LAI) are generally local and are obtained by transforming public domain RS data. LAI values are necessary to estimate the amount of precipitation intercepted and to distinguish soil evaporation from crop transpiration on the basis of relative land cover. In this study, LAI data were derived from NDVI, obtained from an analysis of NOAA–AVHRR satellite images as described earlier. NDVI was converted to LAI using a linear relationship between NDVI and LAI.

In the Mediterranean climatic zone, the natural vegetation types (e.g., *maki,* a Mediterranean shrub land) show little variation in LAI through the year. The NDVI and leaf area indices for maki, the nonirrigated crops and coniferous forests all peak in April at the end of the rainy winter season. The high LAI peak in May for coniferous forest is probably enhanced by deciduous trees within some of the coniferous forests. For the irrigated crops, peak LAI values are reached during the July–August irrigation season.

Soils

Soil characteristics such as infiltration rate, water-holding capacity, wilting point, field capacity, groundwater levels and layering are important in terms of hydrological processes. However, it is much more common to find the available soil data in a descriptive form, using a soil classification based on pedogenetic properties, rather than in the form of quantitative soil physical properties required for modeling activities. A lot of effort has been exerted to transform the easily obtainable soil characteristics into the required physical properties by using the so-called pedo-transfer functions. At the global scale (figure 2) only the FAO soil map of the world is available. However, the scale of this dataset is too coarse (1:5,000,000) to be really useful for basin-scale analyses. RS techniques to obtain soil characteristics are still limited, as most of these techniques are only able to detect earth surface properties, while the required soil characteristics should also reflect the subsoils. Even radar techniques are only able to detect soil moisture contents in the top 10 cm, which reflects more the meteorological conditions at the soil-atmosphere interface than the characteristics of an entire soil profile.

In the case of the Gediz basin, a soil map was available with an appropriate resolution (1:200,000) for basin-scale analysis, including information about soil groups and soil depths. Moreover, for each soil group, a representative profile was analyzed and, for each horizon, texture, bulk density and organic matter content were derived in the laboratory. Simulations performed at the field and irrigation-scheme levels require soil hydraulic functions, water retention and hydraulic conductivity properties. Pedo-transfer functions were used to derive these difficult-to-measure soil hydraulic functions from data such as texture and bulk density (Tietje and Tapkenhinrichs 1993).

Meteorological Data

Meteorological data may be obtained from local climate stations or from global databases. The models used required daily data for temperature, precipitation, dew point (relative humidity), wind speed and sunshine hours (or radiation). For the basin-scale model, average data for each subbasin were derived using Thiessen polygons and adjusting for differences between the elevations of the climate stations and the average elevation of the subbasin. Lapse rates for temperature and dew point were 0.75 ^{o}C/100 m and 0.15 ^{o}C/100 m, respectively, and a change of 2%/100 m of precipitation with elevation was used. For the irrigation scheme and field-scale model the nearest climate station was used, which was always located within a distance of 20 km.

SLURP Basin Model

Model Description

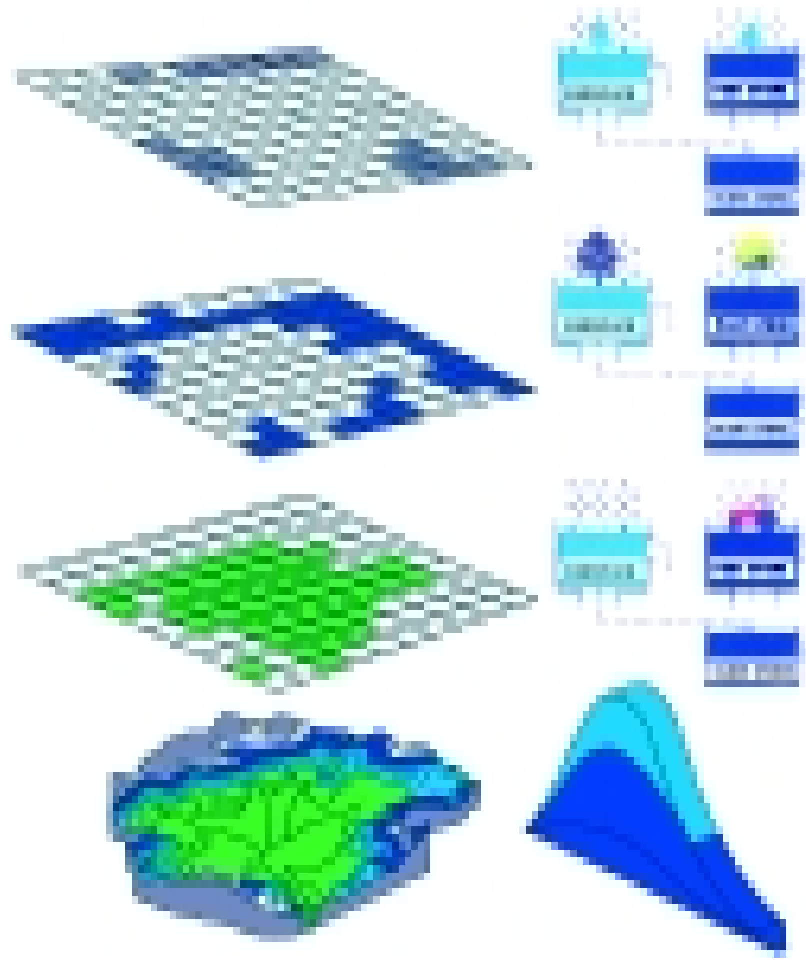
Introduction

SLURP (Semi-Distributed Land Use-Based Runoff Processes) is a conceptual model that, although normally used in semi-distributed form, is capable of being used as a fully distributed hydrological model (Kite 1997). The first version (1975) was developed for use in meso-scale Canadian basins as an alternative to the use of larger and more complicated models.

The major advantage of semi-distributed models such as SLURP is that they can incorporate the necessary physics while retaining comparative simplicity of operation. When SLURP is used in a semi-distributed form, the model is able to simulate the behavior of a basin at many points and in many variables while avoiding the data and computation-hungry excesses of the fully distributed models.

In the SLURP model, the basin is divided into subbasins on the basis of topography. Each subbasin is known as an Aggregated Simulation Area (ASA) since, in turn, it is subdivided into subareas of different land use (figure 3). The ASA used in the SLURP model is therefore a grouping of smaller areas each of which has known land cover properties. For example, land cover may be measured by satellite images for pixels as small as 10 m but it would be impracticable for a hydrological model to operate at such a pixel dimension for a macro-scale basin. Instead, the pixels are aggregated into areas that are more convenient for modeling.

FIGURE 3.
Applying the SLURP model to each land cover within a subbasin.



The basic requirements for an ASA are that the distributions of land covers and elevations for elements (pixels) within the ASA should be known and that the ASA should contribute runoff to a definable stream channel. The latter requirement is also an operational consideration since it means that the stream system within the basin must be at a level of detail such that each ASA contains a defined stream connected to the basin outlet. In SLURP, this is achieved by using automated delineation of the channel network from digital elevation data with the program TOPAZ. The number of ASAs used in modeling a basin will depend on the size of the basin and the scales of data available. The SLURP model may use an unlimited number of ASAs and an unlimited number of land covers per ASA, potentially dividing a basin into very many subareas. To be sure of stability when calibrating, the number of ASAs should equal or exceed the number of land covers. To calibrate the model at least one of the ASAs must have a streamflow gauge at the outlet. The Gediz basin was initially divided topographically into 12 ASAs. Irrigation schemes were then added as separate ASAs to give a total of 27.

Land cover data are commonly derived from satellite images and are used in SLURP as an indicator of climatic zone, vegetation type, soil characteristics, and physiography. The close relationship between land cover and soil characteristics is illustrated in figure 4 for the Gediz basin. Figure 4a shows the distributions of land covers (upper) and soil-water-holding (SWH) capacity (lower). The SWH capacity was derived by combining soil depth, soil-water-field capacity and wilting point data from an existing soil map. The information in figure 4a was used to plot, in figure 4b, the distributions of SWH capacity for each land cover. As expected, the land class “irrigated” occupies soils with high water-holding capacity, the “nonirrigated” agriculture is spread across a range of soil types and the “maki” and “coniferous forest” land covers occupy poor soils with limited water-holding capacity. This embedded use of land cover information makes the SLURP model particularly useful for studies in which land cover is expected to change; for example, in climatic change studies. SLURP has the ability to work with land covers that may change any number of times throughout a model run.

At each time increment, the model is applied sequentially to a matrix of ASAs and land covers. Each element of the (ASA x land cover) matrix is simulated by four nonlinear reservoirs

FIGURE 4A.
Distributions of land cover (upper) and SWH capacity (lower) for the Gediz basin, western Turkey.

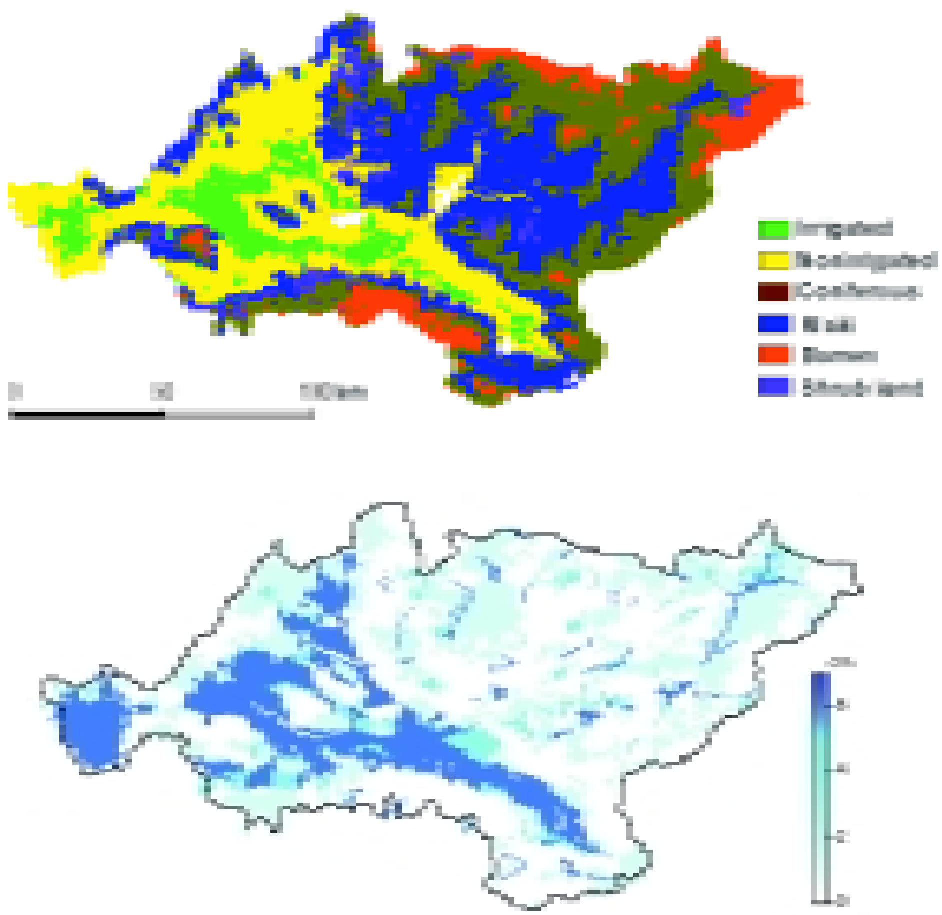
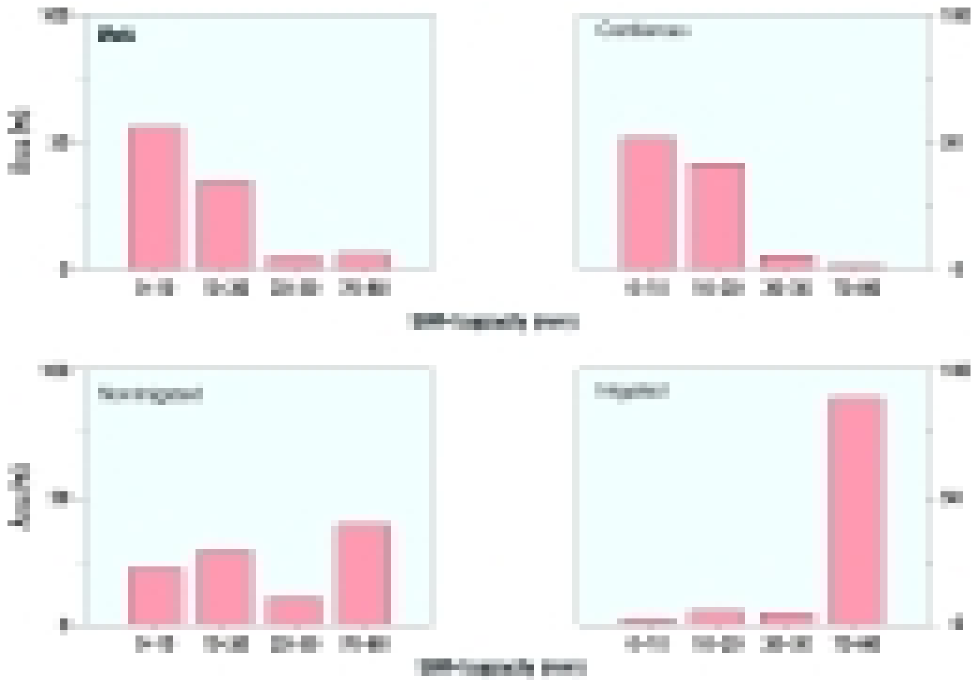


FIGURE 4B.
Distributions of SWH capacity for land covers for the Gediz basin, western Turkey.



representing canopy interception, snowpack, rapid runoff (may be considered as a combined surface runoff and interflow) and slow runoff (may be considered as groundwater). The model routes precipitation through the appropriate processes and generates outputs (evaporation, transpiration, surface runoff, interflow and groundwater discharge) and changes in storages (canopy interception, snowpack, fast store and slow store). Runoffs are accumulated from each land cover within an ASA using a time/ contributing area relationship for each land class and the combined runoff is converted to streamflow and routed down the basin.

A key concept in the development of the SLURP model is that it was designed to make maximum use of remotely sensed data. In addition to using land cover information from Landsat or NOAA satellite, the SLURP model may also use NOAA–AVHRR visible and infrared data to augment the calculation of snow extent. Data from the US Defence Military Satellite Program Special Sensor Microwave Instrument (DMSP SSM/I) satellite may be used to compute average snow water equivalent over each ASA. This use of satellite data is particularly helpful in applying the model to macro-scale basins where sufficient land-based data may not be available.

Applications of SLURP have been published for basins varying in size from prairie sloughs measured in a few hectares (Su, Stolte, and van der Kamp 1997) to a macro-scale basin of 1.8 million square kilometers (Kite, Dalton, and Dion 1994).

The SLURP model allows a choice between four different methods of calculating evaporation from soils, and transpiration from vegetation. The first of these four methods uses the complementary relationship areal evapotranspiration (CRAE) model (Morton, Ricard, and Fogarasi 1985). In most hydrological models and general circulation models (GCMs) actual evapotranspiration is a positive linear function of potential evapotranspiration. In CRAE, on the other hand, the actual evapotranspiration and the potential evapotranspiration are complementary; the argument being that a high potential means a low actual evapotranspiration and, conversely, a low potential means that the actual evapotranspiration is already high. For example, in a desert there will be a high potential but no actual evapotranspiration whereas in an irrigated area surrounded by desert there will be a high actual evapotranspiration and a low potential.

The second, (Granger) method for estimating evapotranspiration is also based on a feedback mechanism and takes into account land cover and vegetation (Granger 1995). This method can be adapted to use RS data. The third option is to use the Spittlehouse and Black method (Spittlehouse 1989), which uses the more conventional Priestley and Taylor method and introduces a soil moisture limited evapotranspiration. Fourth, the FAO version of Penman-Monteith is used in the implementation as used in the SWAP model (Van Dam et al. 1997).

In all four methods the overall evapotranspiration from a land cover is computed as evaporation from the canopy and soil surface, and transpiration from the vegetation in proportion to the ratio of soil-covered and vegetation-covered areas. The soil and vegetation areas are determined by leaf area indices, which may be derived from remotely sensed data. In the Gediz study, the Penman-Monteith method was used to allow easy comparison with evapotranspiration estimates from the SWAP model.

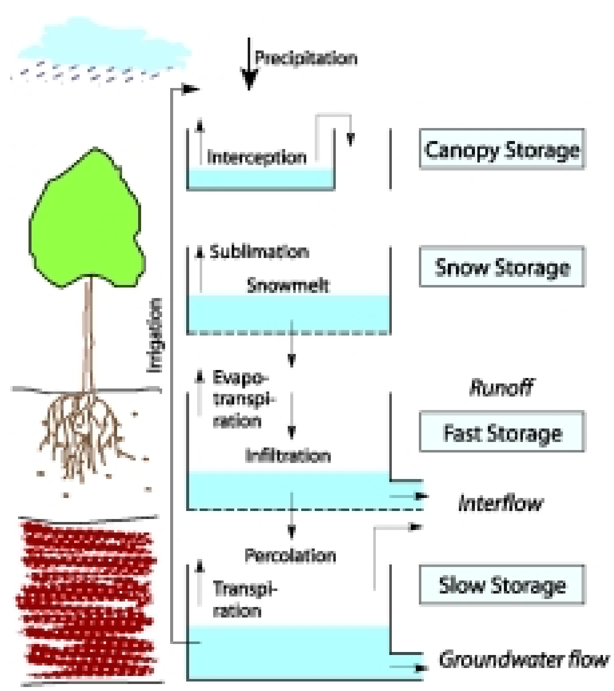
The Vertical Water Budget

Figure 5 shows a simplified flow chart of the vertical water balance that the SLURP model applies to each element of the matrix of ASAs and land covers (except for a water "land cover," which is treated differently). Model parameters include the initial contents of the stores, the maximum infiltration capacity, and retention constants and maximum capacities for both the fast and slow stores. The vertical water balance in SLURP assumes that each ASA has precipitation data derived either externally from an atmospheric model or radar system, or internally from climate station data with Thiessen weights and lapse rates. Optionally, the precipitation data may be modified by the percentage of the ASA covered by cloud, as derived from NOAA–AVHRR visible and near-infrared satellite data.

The vertical water balance operates at a daily time step. The sequence of operations is:

- The daily precipitation, mm, for an ASA is adjusted to the mean elevation of the land cover using a specified percent change per 100 m. There is a 50 percent ceiling on the maximum percent increase in precipitation. Because each land cover occupies a

FIGURE 5.
Outline of the vertical water balance of the SLURP model.



particular range of elevation, a correction factor is also included. This should normally be set to 1.0 but may be used to compensate for a known gauge undercatch.

- The maximum canopy capacity for each land cover is computed as the product of a user-specified maximum depth of leaf water storage, mm, and the leaf area index (LAI). The canopy store is filled from intercepted precipitation. The model initially sets the interception rate proportional to the ratio of actual LAI to maximum LAI. Interception is limited by the maximum canopy capacity.

- Daily values of LAI are interpolated from beginning-of-month values specified for each land cover. LAI may be either measured or estimated from satellite measurements of vegetation growth. The satellite technique is still the subject of research but generally uses visible and near infrared reflectances from polar-orbiting satellites such as Landsat or NOAA to estimate a vegetation index such as NDVI (Normalized Difference Vegetation Index). NDVI must then be converted to LAI for each vegetation type. For SLURP, the beginning-of-month LAI is computed by analyzing 10-day NDVI data published on the internet by the USGS [2]. For each land cover, a linear relationship between NDVI and LAI is assumed, based on the maximum and minimum values of NDVI measured in a series of images.

- Intercepted water is evaporated from the canopy. Land cover albedo is input by the user and canopy resistance for crops varies from 30 s/m for arable crops to 150 s/m for forest.

- The mean daily air temperatures are derived for each land cover in each ASA by adjusting for elevation using a vertical lapse rate in two stages. First, ASA-average temperatures are derived from climate station data or atmospheric model data and, second, these temperatures are converted to temperatures for specific land covers. If the mean air temperature for the land cover is above a critical temperature then any precipitation is assumed to be rainfall and excess precipitation after canopy interception falls to the ground. The critical temperature should be set initially to 0 °C. However, as average lapse rates are used and as not all the pixels of a particular land cover will be at the same elevation, some minor adjustment above or below 0 °C may be necessary. Setting the critical temperature to a small positive value will increase the percentage of precipitation that occurs as snow. The dew point is lapsed to specific land covers at 20 percent of the rate used for air temperature.

- If the daily mean temperature is equal to or below the critical temperature then precipitation is assumed to be snowfall and any excess precipitation from the canopy store is added to a snowpack. Land cover albedos used in evaporation calculations can be adjusted for the effects of snow on the land cover. The snowpack albedo is set to 0.80 initially and reduced exponentially each day until a minimum of 0.40 is reached or until the snowpack is melted or sublimated. If fresh snow falls, the albedo is reset to 0.80.

- The snowpack may be depleted by snowmelt in two ways. First, a simple degree-day approach may be used in which melt depends only on a melt rate, mm/day/°C, and the temperature in degrees above a defined critical temperature. In SLURP, the snowmelt rate on any day is calculated using a parabolic interpolation from values specified for each land cover on January 1st and July 1st. Despite its simplicity, the degree-day method of snowmelt is not easily improved upon, even by a full energy balance approach.

Second, SLURP may use a simplified energy budget method. In this algorithm, the melt rate depends on both temperature and net radiation. A different value of albedo is used for each land cover to allow for the different proportions of radiation intercepted by the various heights of vegetation. If hours of bright sunshine or global radiation data are used, the net radiation needed for snowmelt will be computed internally.

Climate change scenarios, such as those generated by GCMs for increased atmospheric greenhouse gases, change not only air temperatures but also cloud cover, and hence net radiation. The advantage of the simplified energy budget method is that it allows changes in temperature and net radiation independently. This may be useful to evaluate the effects of a climate change scenario on hydrology and water resources.

Snowpack, in terms of snow water equivalent (SWE), may also be input directly to the model from snowcourse data or computed from passive microwave satellite data. It was found for a mountain basin (Slough and Kite 1992), that data from individual snowcourses are not good estimates of ASA averages. SWE values computed from passive microwave data, on the other hand, provide better estimates because they themselves are average values from large areas (e.g., 25 km x 25 km for data from the DMSP satellite). In addition, the microwave data are available in all weathers and at frequent sampling intervals.

Snowmelt may, optionally, be modified by the areal extent of snow cover from NOAA–AVHRR images.

- The subsurface flow processes are simulated using two linear reservoirs, the rapid store, which may be considered as an aerated soil layer and the slow store, which may be considered as a groundwater zone. Rainfall and any snowmelt infiltrate through the surface into the rapid store depending on the current infiltration rate, the current contents of the rapid store, the maximum capacity of the store and the maximum possible infiltration rate. If the water supply is higher than the allowable infiltration or the rapid store is full, the water excess is treated as surface runoff.

- LAI is used to determine the percentages of bare soil and vegetation for each land cover. Evaporation from the soil surface is then removed from the fast store.

- The fast store also generates outflow. The outflow is separated into percolation and interflow depending on the current contents and the maximum possible contents of the slow store. The percolation is added to the contents of the slow store.

- The slow store then generates groundwater flow depending on a retention constant. If overflow from the slow store occurs it is treated as interflow.

- Plant transpiration is extracted from the slow store depending on the LAI. The stomatal efficiency of vegetation, which varies with atmospheric CO_2 level, may be specified for each land cover.

SLURP treats lakes and reservoirs within an ASA in two different ways. If the lake or reservoir has regulation or routing specified, then the vertical water balance will be carried out as part of the regulation or routing as described later. If, on the other hand, the water in an ASA represents only a small unregulated lake or even a collection of small water bodies, then the vertical water balance is carried out as for any other land cover except that some of the parameters are changed to eliminate the functions of the canopy store and the fast store and to ensure that evapotranspiration from the slow store is assigned to evaporation and not transpiration.

Routing

Runoff, interflow and groundwater flow from each land cover are combined and, first, routed to the nearest stream and then routed down the stream channel to the ASA outlet. In a fully distributed model this routing would be done for each grid square or pixel of the basin. In the semi-distributed approach taken in SLURP we compute the distances for each pixel and then fit normal probability distributions to the to-stream and downstream distances. The distances and changes in elevation to the to-stream and down-stream are computed using the topographic analysis program, TOPAZ, from digital elevation data. The SLURPAZ program (Lacroix and Martz 1997) then processes the physiographic outputs from TOPAZ together with land cover data into input files for the SLURP model.

- The water velocities for to-stream travel are computed using Manning's equation with a different coefficient of roughness for each land cover, assuming that the hydraulic radius is a small number for wide shallow flows. The minimum and maximum to-stream travel times are then computed for each land cover using the velocity, with distances computed as the mean plus and minus two standard deviations from the probability distributions. Travel times downstream to the ASA outlet for each land cover are computed from the mean distances downstream, the changes in elevation downstream and the stream velocities. Total travel times are the sums of the to-stream and the downstream travel times. The total travel times are used in a lognormal smoothing filter to distribute the runoff from each land cover over time. The results are weighted by the percentages of the ASA covered by each land cover, converted to m^3/s, and added to the total flow of the ASA.

- Outflows are routed from an ASA to the outlet of the next ASA down the stream system, and so on until all the flows arrive at the outlet of the basin. The user may choose to simply accumulate the flows from each ASA with no delay or attenuation or may choose between Muskingum routing or Muskingum-Cunge routing depending on data availability.

- If an ASA contains a lake for which the stage-storage and stage-discharge relationships are known, these may be used to simulate the lake effect on the hydrograph. Similarly, SLURP can simulate the actions of reservoirs for which the regulation plans are known. For very large lakes, the heat storage in the lake causes a lag in the annual evaporation cycle. To account for this the user can specify the use of the Morton lake model.

Diversions

In many basins, regulation structures exist to divert water from the river for hydropower, water supply or irrigation. Water diverted from an ASA may be used as irrigation water for any land cover in any downstream ASA. Any diverted water remaining after irrigation will be added to the outflow from the irrigated ASA. The user may also specify a minimum allowable river flow for environmental or dilution purposes. If this minimum flow is not zero, any specified diversions will be reduced as necessary to maintain this minimum flow in the main river.

As an example, figure 6 shows the arrangement of reservoirs, diversions and irrigation schemes used by the SLURP model to simulate the water resources of the Gediz basin.

Interventions in the Vertical Water Balance

The vertical water balance described earlier is for a natural system. However, water diverted from the river and applied as irrigation will modify the natural water balance, and SLURP accounts for this as an intervention in the vertical water balance for a particular crop. Irrigation water as well as water for urban or industrial supplies may also be extracted from groundwater, another intervention in the vertical water balance. Such interventions are specified by starting and ending dates, by source of water (canal or groundwater) and by type of application (furrow irrigation, sprinkler irrigation, urban or industrial consumption or water export).

Outputs from the Model

Three types of output are available from the SLURP model: state variables such as groundwater content or snowpack, distributed fluxes such as evaporation and transpiration and point data such as streamflow.

The distributed fluxes are available for each land cover within each ASA for each day of the model run. For example, figure 7 shows the distribution of annual transpiration across the Gediz basin for 1990.

Simulated streamflow may be output at many points in the basin and could be used for forecasting, or for checking minimum supplies. For example, figure 8 shows simulated inflows to the Demirköprü reservoir for 1990. Note that the computed inflow to the reservoir is higher than the observed inflow during the summer period. This is probably because there are water extractions for irrigation, which are not accounted for in the irrigation statistics used in the model.

FIGURE 6.
Flow chart of the Gediz basin reservoirs, regulators and irrigation schemes.

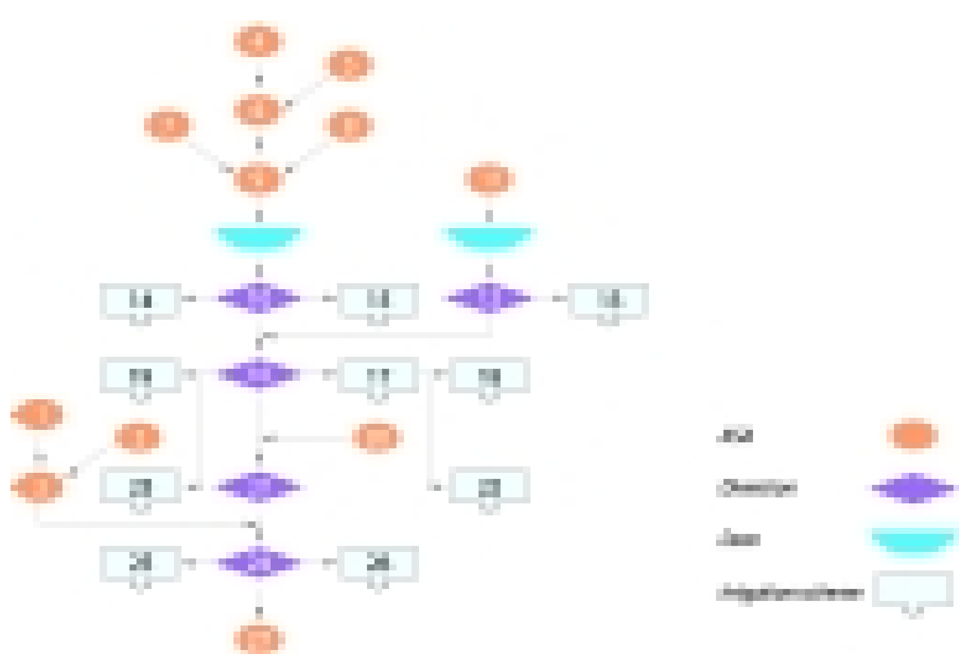


FIGURE 7.
Annual transpiration, the Gediz basin, 1990.

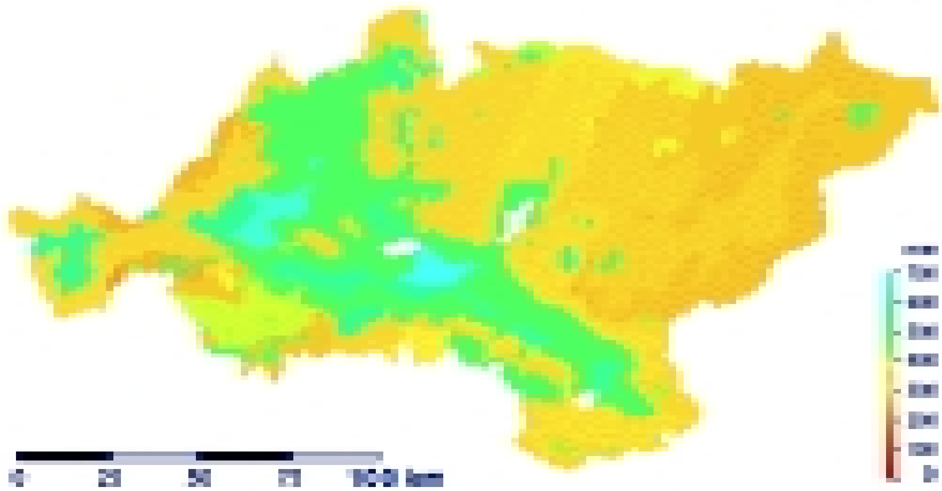
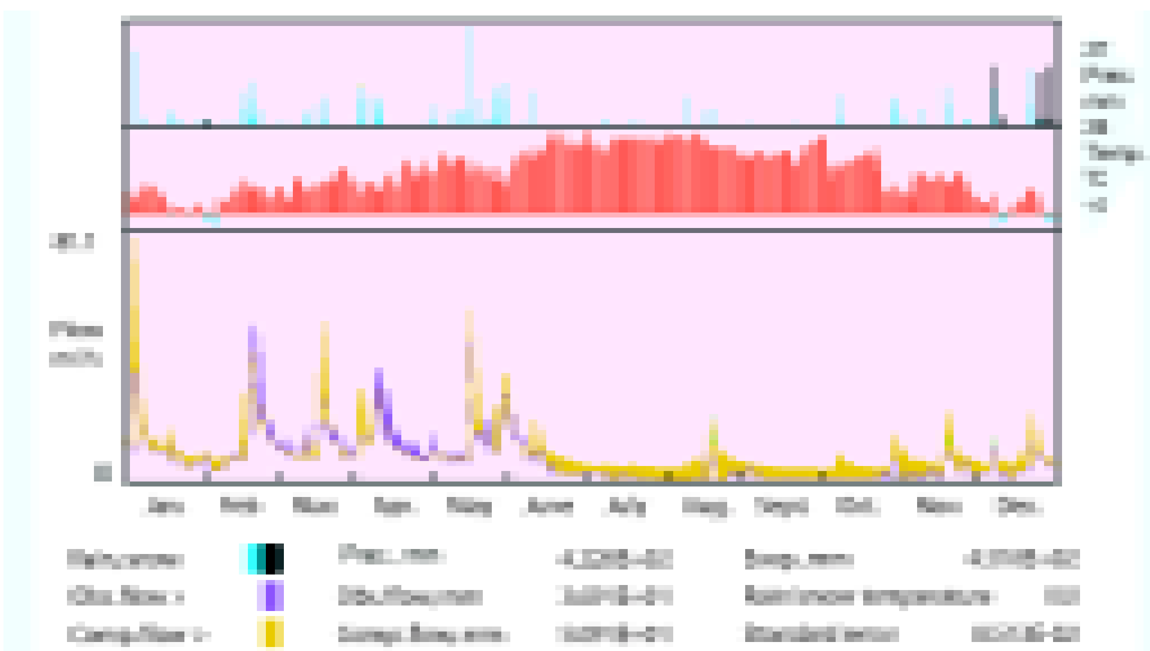


FIGURE 8.
Simulated inflows to the Demirköprü reservoir, 1990.



Note: Prec. = precipitation; Temp. = temperature; Evap. = evapotranspiration; Obs. = observed; and Comp. = computed.

SWAP, Detailed Agro-Hydrological Model

Model Description

Introduction

SWAP (Soil-Water-Atmosphere-Plant) is a one-dimensional physically based model for water, heat and solute transport in the saturated and unsaturated zones. SWAP also includes versatile modules for simulating irrigation practices and crop yields. The water transport module in SWAP is based on Richard's equation, which is a combination of Darcy's law and the continuity equation. A finite difference solution scheme is used to solve Richard's equation. Crop yields can be computed using a simple crop-growth algorithm based on the FAO procedure or by using a detailed crop-growth module based on the partitioning of produced carbohydrates between the different parts of the plant, considering the successive phenological stages of the plant. Actual soil evaporation (E) and crop transpiration (T) are simulated, based on the potential evapotranspirative demand and the LAI development. Actual transpiration and evaporation are obtained according to the actual available soil moisture in the top layer or root zone for evaporation and transpiration, respectively. Finally, irrigation can be prescribed at fixed times or scheduled according to different criteria.

SWAP was developed by the University of Wageningen and the Winand Staring Centre in Wageningen, the Netherlands. The first version of SWAP, called SWATR, was developed more than 20 years ago (Feddes, Kowalik, and Zaradny 1978). Since then, many studies have been successfully conducted using the SWATR model and its successors to study SWAP relationships in many parts of the world. The description of the model given here is general; a more detailed description can be found in Van Dam et al. 1997.

Water Transport

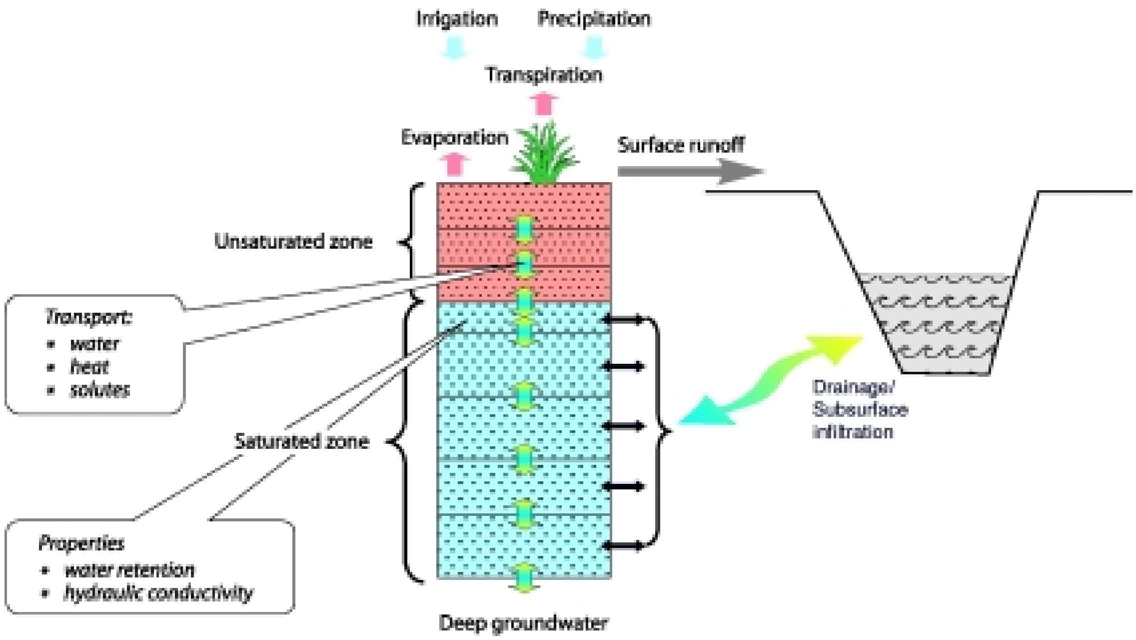
An overview of the SWAP model is given in figure 9. The core part of the program is the vertical flow of water in the unsaturated-saturated zone, which can be described by the well-known Richard's equation. This equation combines Darcy's law and the continuity equation which lead to a partial differential equation. To solve this equation a finite difference scheme with explicit linearization is used by the program. To apply this finite difference scheme thin soil layers must be defined ranging from 1 to 2 cm in the top soil, where dynamics and gradients are high, to 25 cm at the bottom of the profile.

Small layers are combined to horizons and for each horizon the soil hydraulic properties, retention curve and conductivity curve must be known. As the measurements of these properties are labor-intensive and require special laboratory equipment, especially for the hydraulic conductivity, pedo-transfer functions can be used. These functions transform the easily obtainable soil properties, such as particle size distribution and bulk density, to the required soil hydraulic functions.

Upper Boundary Condition

The upper boundary condition consists of the climate data and the irrigation inputs. The latter will be described in a subsequent section. Climate data can be obtained from meteorological stations and should include at least precipitation and potential evapotranspiration. If a crop is present, or soil temperature is to be simulated, the minimum and maximum air temperatures must be defined. If the detailed crop growth module is used, global radiation must also be included.

FIGURE 9.
Overview of the agro-hydrological model SWAP.



As an alternative to including the potential evapotranspiration directly as input, SWAP can calculate three potentials: (i) potential T for a wet crop, (ii) potential T for a dry crop, and (iii) potential E for a wet, bare soil. These three potentials are calculated by varying the values for crop resistance, crop height and albedo in the Penman-Monteith equation. Subsequently, the interception content and the LAI are used to determine the distribution of these three potentials.

A piecewise linear reduction function is assumed between potential transpiration and soil moisture availability. This function defines five different stages of root water uptake: (i) no water uptake due to oxygen deficit, (ii) a transition zone between oxygen deficit and unlimited uptake, (iii) an unlimited uptake, (iv) a transition zone between this unlimited uptake and water shortage, and (v) no uptake due to water shortage. The threshold values for these five stages depend on the crop and the soil type. Data can be taken from field or laboratory experiments or from the literature.

Actual soil evaporation can be estimated using Richard's equation using the potential E as the upper boundary condition. However, this requires information about the soil hydraulic properties of the first few centimeters of the soil, which are hardly measurable and are highly variable in time as a consequence of rain, crust and crack formation, and cultivation processes (Van Dam et al. 1997). All these processes reduce the actual E in comparison with the values obtained by applying Richard's equation. Therefore, an additional reduction was included whereby the actual E is a function of the potential E, the soil moisture content of the top soil, an empirical soil specific parameter, and the time since the last rainfall.

Lower Boundary Condition

The SWAP model offers a broad range of lower boundary conditions to be selected by the user. These can be generalized into three types: flux-specified, pressure-head specified and flux-groundwater-level relationships. The most appropriate criterion must be selected, depending on the local condition and the availability of data. For the Gediz basin two conditions were used: a fixed groundwater depth and a flux-dependent groundwater level. The latter case calculated the flux to or from an aquifer as a function of the groundwater level and the resistance of a semi-confining layer.

Irrigation Inputs

Two different types of irrigation can be specified in SWAP. Either a fixed irrigation can be specified, or an irrigation can be generated according to a number of criteria. A combination of fixed and calculated irrigations is also possible. An example of this would be a fixed irrigation (land preparation) before planting and scheduled irrigations based on soil-moisture conditions after planting. Fixed irrigations can be applied the whole year-round, but calculated irrigation can only be active during a cropping period. Both types of irrigation may overlap, but fixed irrigation has priority.

For both fixed and calculated irrigations, the user can specify whether it will be applied as surface or sprinkler irrigation. The main difference between these methods is that with sprinkler irrigation the model assumes water will be first intercepted by vegetation before it reaches the soil.

For fixed irrigation, only the application day and the depth of application must be defined. If the user wants to include salinity in the analyses, the salt concentration of the irrigation water also has to be given.

For scheduled irrigation, five different timing criteria can be chosen: (i) allowable daily stress, (ii) allowable depletion of readily available water (i.e., field capacity minus temporary wilting point), (iii) allowable depletion of totally available water (i.e., field capacity minus permanent wilting point), (iv) allowable depletion amount, and (v) critical pressure head or moisture content exceeded. In all these five cases the model defines the starting day of irrigation. The amount of water applied at this specific day should also be defined. Two options are possible here: fixed irrigation depth and 'back-to-field capacity.'

The fixed irrigation depth is generally used when gravity irrigation systems are simulated, which generally allows little variation in application depth. It is possible to specify the irrigation amount depending on the development stage of the crop. The 'back-to-field capacity' option is useful in the case of sprinkler or micro irrigation. In this option the profile is brought back to field capacity, depending on soil moisture calculations. An over-irrigation (positive) or under-irrigation (negative) amount can be specified depending on the crop development stage. This can be useful if salts need to be leached (over-irrigation) or regular rainfall (under-irrigation) is expected. This also provides opportunities to evaluate deficit irrigation.

Crop Growth

Crop growth can be simulated using a simple crop growth algorithm based on the FAO procedure or by using a detailed crop growth module based on the partitioning of the generated carbohydrates between the different parts of the plant, considering the successive phenological stages of the plant. For the detailed module, a distinction can be made between a grass crop, which assumes regular mowing of the sward, a constant vegetative stage and a regular crop.

The simple crop-growth model is useful if accurate simulation of crop water use is more important than accurate simulation of crop yield. It represents a green canopy that intercepts precipitation, transpires and shades the ground. The user specifies LAI, crop height and rooting depth as a function of the development stage. Instead of LAI, soil cover fraction might be used to divide potential evapotranspiration into potential transpiration and potential evaporation. Crop development can either be controlled by the cumulative temperature starting from seeding or planting the crop, or can be linear in time. The LAI is used to calculate rainfall interception. The crop height is only used by SWAP to determine the aerodynamic resistance in the Penman-Monteith equation. At each growing stage, the yield response factor determines the relationship between the relative yield and the relative transpiration (defined as the ratio of the actual transpiration to the potential transpiration). If information on the yield response factor is lacking a factor of 1 can be assumed. Both the water and the salinity stress will limit the potential transpiration of the crop. SWAP assumes that the reduction factors due to water and salinity stress can be multiplied to derive the total reduction.

For the detailed crop model, the crop growth part of the simulation model WOFOST is used (Van Diepen et al. 1989). In WOFOST the daily dry matter increase is calculated as the production of assimilates minus the respiration losses. This dry matter increase is partitioned to the major plant organs: roots, leaves, stems and storage organs. The rates of these processes and the pattern of dry matter distribution are determined by the crop status and its response to controlling environmental conditions. The crop growth curve and the resulting yield level are found by integrating the daily dry matter increase, partitioned to the plant organs, over the total crop-growth period. Crop growth is simulated over the period from emergence to end of active growth (maturity) with time steps of one day.

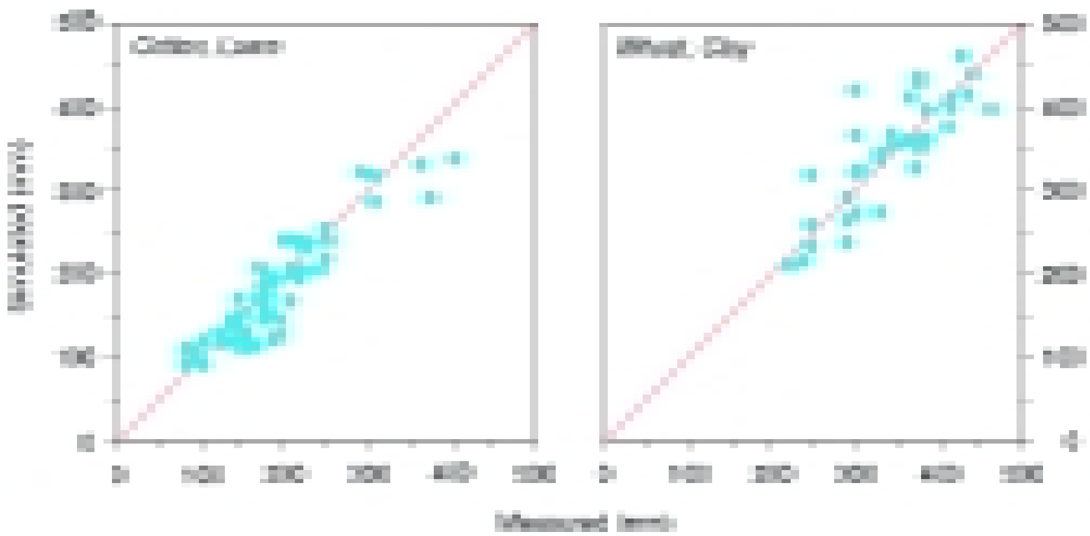
SWAP Model Applications

Model Validation

Although the SWAP model itself has been tested many times, we have validated the performance of SWAP for this particular case and dataset. Two on-farm experiments, each including five different irrigation scheduling applications, were conducted in 1997 to evaluate the response of cotton and winter wheat to different water management practices. The cotton experiment was performed on a loam soil and the wheat experiment on a clay soil. Different volumes of irrigation water were supplied at different development stages of the crops. The amount of irrigation ranged from 0 (no irrigation) to 660 mm for cotton and 393 mm for wheat. The resulting soil-moisture profiles were measured. As no observations of water table depths were available, they were obtained by minimizing the difference between measured and simulated moisture contents.

Measured and simulated soil-moisture contents for the top 90 cm are shown in figure 10 for the wheat and cotton experiments. The measured and simulated soil-moisture contents are comparable and the coefficients of determination (r^2) are 0.84 and 0.67 for the cotton and the wheat experiments, respectively. The simulated moisture contents show no systematic underestimation or overestimation of the measured moisture content, except for the higher moisture content for the cotton experiment where the simulated values are somewhat lower than the measured values. The scatter for the wheat experiment was somewhat more, probably due to the clay soil, which has some small cracks causing some irregular infiltration flow patterns. The overall agreement was such that the model was considered to be adequately validated to be used in this particular case.

FIGURE 10.
Observed and simulated soil-moisture content for a depth from 0 to 90 cm.



Understanding Evapotranspiration

Actual evapotranspiration is an important term of the water balance and actual crop transpiration is considered to be the determining factor in crop production. However, measurements of actual evapotranspiration are complicated and especially the distinction between soil evaporation, which is considered as a loss, and crop transpiration requires specific measurement techniques (Kite and Droogers 2000). The SWAP model was used to get a better understanding of the processes involved in evapotranspiration.

Soil, crop, irrigation, water table and climate data were collected for one field in the Menemen Left Bank (MLB) irrigation scheme during 1998. The MLB scheme is close to the outlet of the Gediz river (left side of figure 7). All these data were input to the SWAP model and actual soil evaporation, crop transpiration and other terms of the water balance were simulated (figure 11). Potential E and T were calculated separately using the LAI to derive the potential rates for E and T. Figure 11 clearly shows low potential T and high potential E as the crop is in its early stage. The difference between potential and actual transpiration during some parts of the growing season, indicates stress as a consequence of diminishing water in the root zone. In particular, a short period before an irrigation application, a drop in actual T can be observed, especially before the second irrigation. Actual E was always lower than potential except for the first few days after rainfall or irrigation when the topsoil was wet.

A detailed picture of simulated soil moisture contents and corresponding ratios between actual and potential T, are displayed in figure 12. Clearly, the farmer was about 5 to 10 days late with every irrigation application for optimal crop performance, especially with the second and third irrigations. The effect of oxygen deficit on the extraction of water by plant roots (figure 12) can be observed during the two rainfall days (days 137 and 139) and on the first few days after the irrigation applications.

FIGURE 11.
Inflows, crop transpiration and soil evaporation of a cotton field in the MLB.

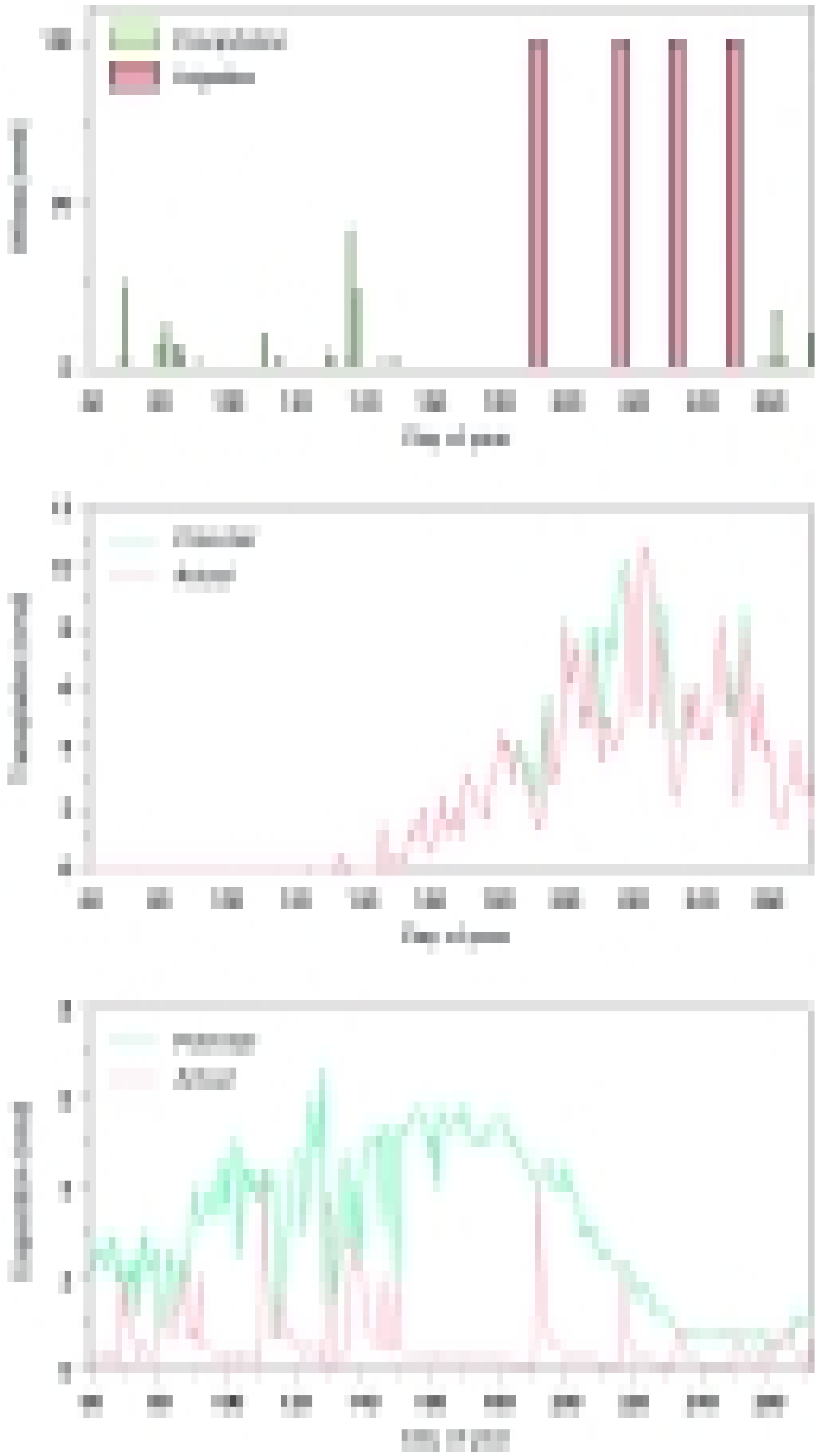


FIGURE 12.
Daily soil-moisture profiles for the cotton site for the whole growing season, and (top portion) the ratio of actual transpiration (T_{act}) to potential transpiration (T_{pot}).

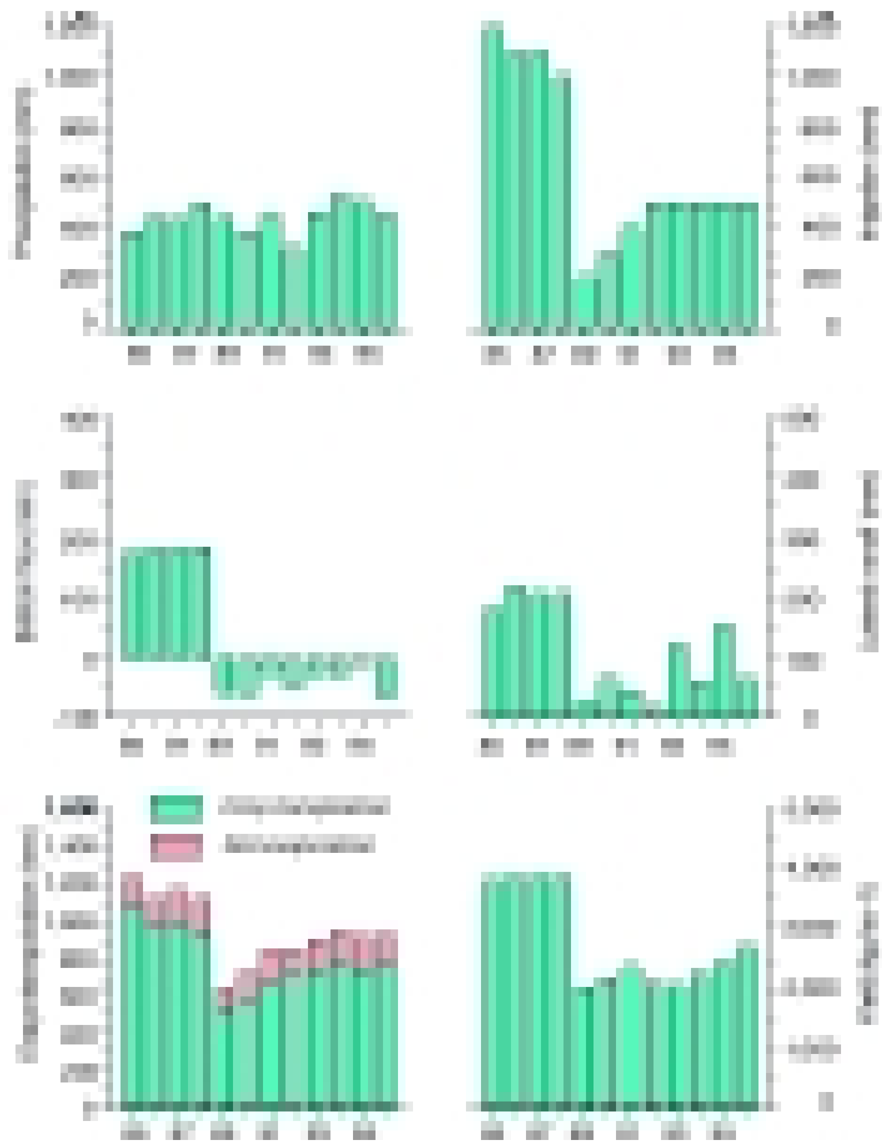
Analyzing Water Balances

A clear understanding of all the components of the water balance is essential to analyze possibilities of water savings in irrigated agriculture. However, most components of the water balance are not easily measurable either in terms of the required time interval or the complexity of the processes. The SWAP model was applied in a distributed manner to reveal all the terms of the water balance for the Salihli Right Bank (SRB), an irrigation scheme located in the middle of the basin (see figure 7). A combination of point data and areally distributed data was used as input for the model.

The whole study area was divided into subareas denoted as Land Use Systems (LUSs) and each LUS was considered to be homogenous. Each LUS is defined by its soil type and its crop, resulting in 20 LUSs. These LUSs are considered to be the building blocks for the simulations, i.e., the whole SRB is modeled as a set of 20 homogeneous areas. The LUSs are considered to have no interaction in terms of groundwater flow as only vertical movement of water was taken into account. Also surface water was not modeled explicitly for the area, but was defined as a boundary condition for the LUS in terms of irrigation water availability.

For one of the LUSs, the annual water balances for a period of 12 years are depicted in figure 13. The drought that started in 1989 is not evident from the precipitation data in SRB. However, precipitation in the higher elevations of the basin show a marked reduction over the drought period. Irrigation inputs before the drought (1989–1992) were dependent on the requirements of the crop since the availability of water for irrigation was not limiting. The assumption was made that farmers started irrigating 100 mm of water as soon as crop

FIGURE 13.
Example of the annual water balances and crop yields for one LUS in the SRB.



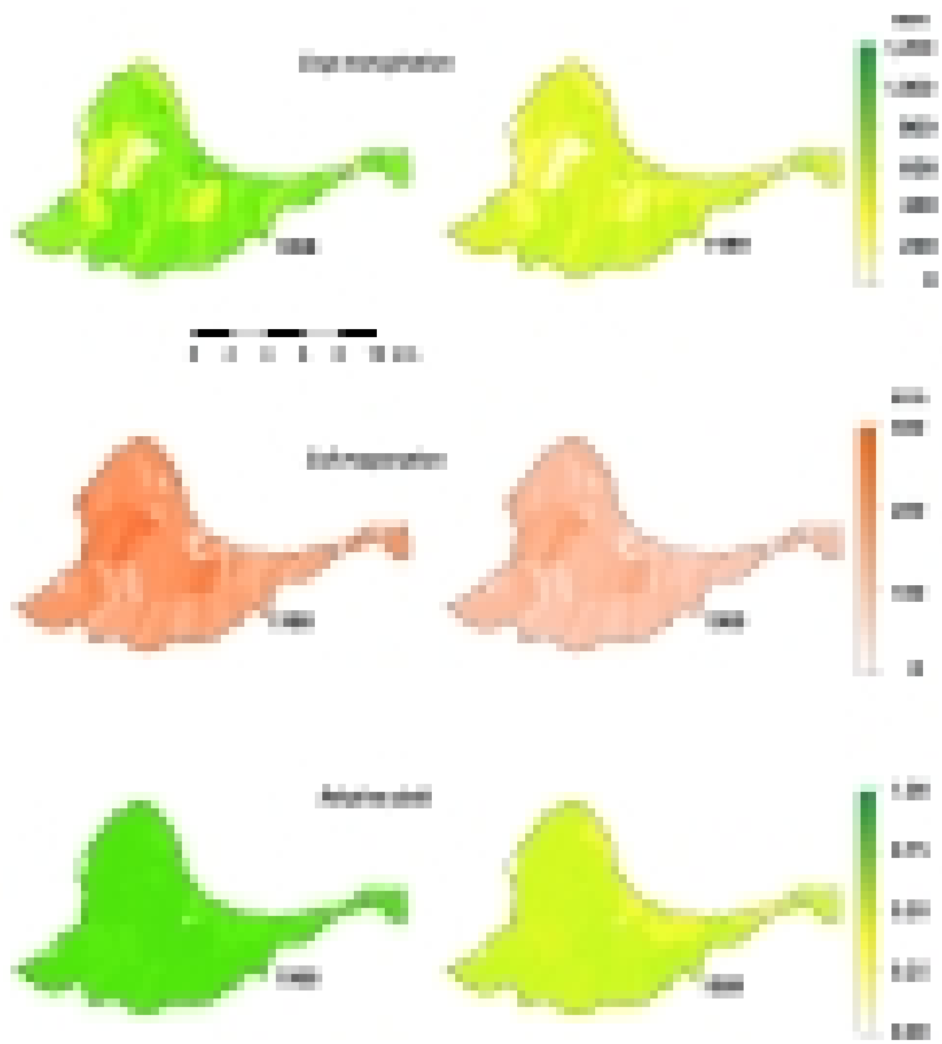
growth dropped below potential. The assumption was also made that when the ratio of actual crop transpiration to potential crop transpiration falls to 0.95 then the farmers start irrigating 100 mm of water. During the drought, crop yields were reduced (by 35%) over the whole irrigation scheme according to the results of the simulation model. According to a survey by the State Hydraulic Works of Turkey (DSI) average yields dropped by 20 percent for cotton (from 2,810 to 2,250 kg ha^{-1}) and 14 percent for grapes (from 5,410 to 4,630 kg ha^{-1}), which are less than the results as estimated by the model. It is probable that farmers had responded quicker to the drought (by using groundwater in the first year of the drought) than was assumed in the model. Bottom flux was upwards (negative in figure 13) for all years after the onset of the drought in

1989, indicating capillary rise from the groundwater into the root zone. This flux could be maintained, as the SRB is located on top of a high-yielding aquifer.

The years 1988 and 1989, representing the pre- and post-drought years, were selected for detailed analyses. Figure 14 shows areally distributed crop transpiration, soil evaporation and relative yield for these 2 years.

Actual transpiration was reduced for all areas in 1989, but by less for the areas that are dominated by grapes. Reduction in transpiration and relative yield was substantial in 1988 compared to 1989. For 1988, relative yield was everywhere about 95 percent, as this was the threshold value to start irrigation. In 1989, simulated relative yields went down to about 60 percent, which is somewhat lower than reported by DSI as explained earlier. Clearly, some soil types are more drought-sensitive than others. In figure 14, the relative yield for grape areas in 1989 can be distinguished as suffering less from water shortage.

FIGURE 14.
Distribution of crop transpiration, soil evaporation, and relative crop yields for the SRB command area.



Linking Models

Introduction

The SLURP and SWAP models have been applied at three different scales: basin, irrigation system and field. The main objectives of applying the models are to understand processes and to evaluate current productivity and alternative scenarios. The scenario evaluation will be described in a subsequent report. Here, results of using the models will be presented to understand processes and to evaluate the productivity of water at the different scales. The productivity of water is based on performance indicators computed from the water balance using inflows and outflows. Such a water accounting system can be considered at different spatial scales: basins, subbasins, irrigation systems or fields. The conceptual framework for water accounting developed by Molden (1997) and Molden et al. (1998), based on inflow and outflows, is mainly followed here.

The water balance for a certain area can be described as:

Precipitation + Irrigation + Capillary Rise + Soil Water Storage Change = Transpiration + Evaporation + Surface Runoff + Drainage + Percolation

From the soil water balance the following performance indicators were calculated:

$PW_{irrigated}$ = Productivity / Irrigation
PW_{inflow} = Productivity / Net Inflow
$PW_{depleted}$ = Productivity / Depletion
$PW_{process}$ = Productivity / Process Depletion

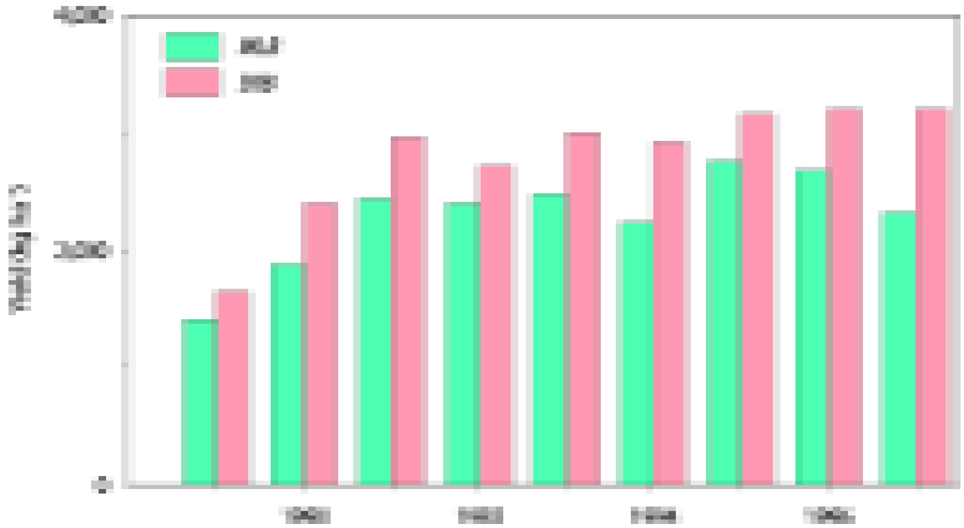
where, PW = productivity of water.

A more detailed description of the concepts of the PWs is beyond the scope of this publication, but can be found elsewhere (Molden 1997; Molden et al. 1998). For the three spatial scales distinguished here, different definitions apply to the performance indicators. $PW_{irrigation}$ is not applicable to the whole basin, as production will also include nonirrigated areas as well as nonagricultural areas such as forests and natural vegetation used for grazing. Net inflow at the basin scale does not include capillary rise, as this is zero for a basin as a whole. The amount of water depleted for a certain area depends on the location of the area considered. Drainage water and water percolated to groundwater can be used by downstream users as long as the water quality is not limiting. However, outflow from coastal areas should be considered as a loss, as this is not used any further. Therefore, the definition of depletion depends on the location of the area considered. Finally, process depletion is defined as the amount of water transpired by the crop.

Field Scale

Simulated yields for two cotton fields are displayed in figure 15, one close to the basin outlet and one in the middle of the basin. The dry period starting in 1989 had a dramatic impact on yields, with a drop in cotton yields of about 50 percent. The crop yields increased in later years as a result of a return to more favorable climatic conditions as well as the use of groundwater extractions for irrigation. The drought in 1989 was a result of reduced irrigation releases (figure 13) due to the low rainfall in the catchment of the Demirköprü reservoir in the preceding 2 years. The rains falling on the systems were more or less constant through the period and lowest in 1992 for the SRB. The effect on yield was small because the reduction in rainfall was over the winter periods and because of the recovery in irrigation inputs.

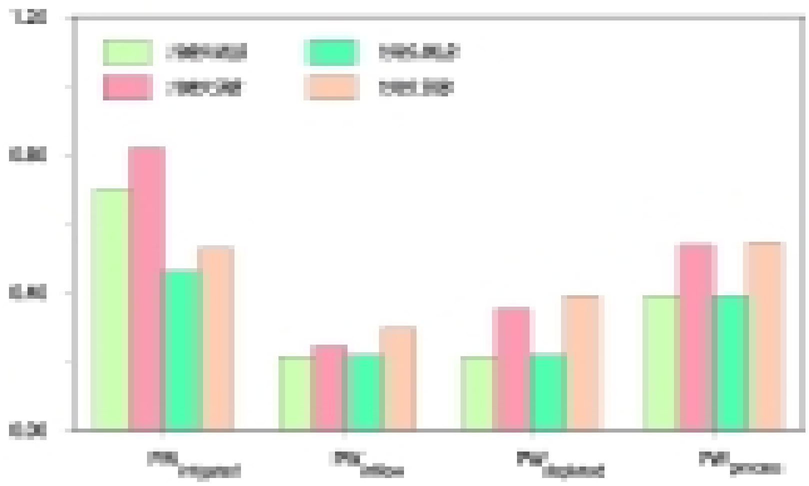
FIGURE 15.
Simulated yields for the two cotton fields. MLB is located at the tail end of the basin and SRB in the middle of the basin.



The two fields also differ somewhat in the yields obtained, although the soil type and crop were identical. Generally, the MLB field has lower yields, mainly as a result of different climatic conditions in terms of higher evaporative demand by the atmosphere as a result of higher wind speeds. It should be emphasized that the crop growth model applied here is a general one based on the ratio of actual transpiration to potential transpiration and a drought sensitivity factor for different crop development stages (Doorenbos and Kassam 1979). Water quality aspects were ignored in this study as no data were available. However, some information indicated that water quality was lower at the MLB, but it is understood that there was no severe water stress to cotton.

The severe drought starting in the upstream part of the basin a few years before 1989 resulted in a dramatic drop in irrigation inputs in 1989. A detailed analysis of the period during and after the drought is interesting, because the irrigation system during these two periods could be considered as ‘demand-based’ and ‘supply-based.’ Figure 16 shows the four PWs for a year directly after the drought (1989) and for a later year when the irrigation input had recovered (1995). Clearly, all the values for the SRB field were higher than those for the MLB field, as explained earlier. PW_{inflow} and $PW_{depleted}$ are similar for MLB as the difference in these factors depends only on the changes in soil water storage. $PW_{irrigated}$ was, as expected, higher for the low irrigation input year (1989) than for the higher input year (1995). This seems to be a justification for applying deficit irrigation: lower irrigation inputs increase the productivity of water. However, as mentioned before, water usage must be considered in a broader sense instead of only water applied for irrigation. $PW_{process}$ should be seen as a real indicator of whether water has been saved. It appears that during the dry year $PW_{process}$ is similar to the value during the wet year, indicating that deficit irrigation does not result in any real water savings. It should be emphasized that the crop growth module used here is an empirical one, which might be less accurate for these dry conditions.

FIGURE 16.
Productivities of water for two cotton fields in a dry year (1989) and a wet year (1995).



Irrigation-Scheme Scale

The SWAP model was applied in a distributed form using the LUSs as described earlier. All the terms of the water balance as well as yields for the whole irrigation scheme were estimated using the model, enabling the calculation of water productivity values. Here, $PW_{irrigated}$ is used as an example, but a discussion of other productivity figures can be found elsewhere (Droogers and Kite 1999).

Figure 17 shows values of yield and $PW_{irrigated}$ distributed across the SRB irrigation scheme for a dry year (1989) and a wet year (1995). The yields show much spatial variation, with high values in areas that are dominated by maize/wheat and low values in areas with a high percentage of uncropped areas. Yields were lower in 1989 as a consequence of the lower irrigation inputs, although the maize/wheat areas suffered to a lesser extent from the drought as the wheat was not irrigated. Also, the grapes suffered less from the drought as the deeper roots induced a higher capillary rise from the groundwater. Differences in the $PW_{irrigated}$ between the 2 years were very high, with areal average values for $PW_{irrigated}$ of 1.11 kg m^{-3} and 0.76 kg m^{-3} for 1989 and 1995, respectively. The lower values in 1995 occurred despite higher yields as a result of substantially higher irrigation inputs. Again, areas with a higher percentage of grapes and maize/wheat show higher $PW_{irrigated}$ values.

Basin Scale

The SLURP model was applied to the whole basin to give the terms of the water balance. The resulting crop yields were computed from these data. The PW_{inflow} defined as the yield divided by the net inflow (precipitation and irrigation) was analyzed for 2 years. Additional PW figures are not discussed here but can be found in Droogers and Kite 1999.

Figure 18 shows yield, actual transpiration, and PW_{inflow} for the whole basin for the dry year (1989) and the wet year (1995). As expected, the irrigated areas have higher transpiration rates than the nonirrigated areas and naturally vegetated areas, inducing higher crop yields. Areally averaged yields were 790 kg ha^{-1} and 1,005 kg ha^{-1} for 1989 and 1995, respectively. It is interesting to note that the irrigation schemes

FIGURE 17.
Areal distribution of yield and $PW_{irrigated}$ for the SRB during a dry year (1989) and a wet year (1995).

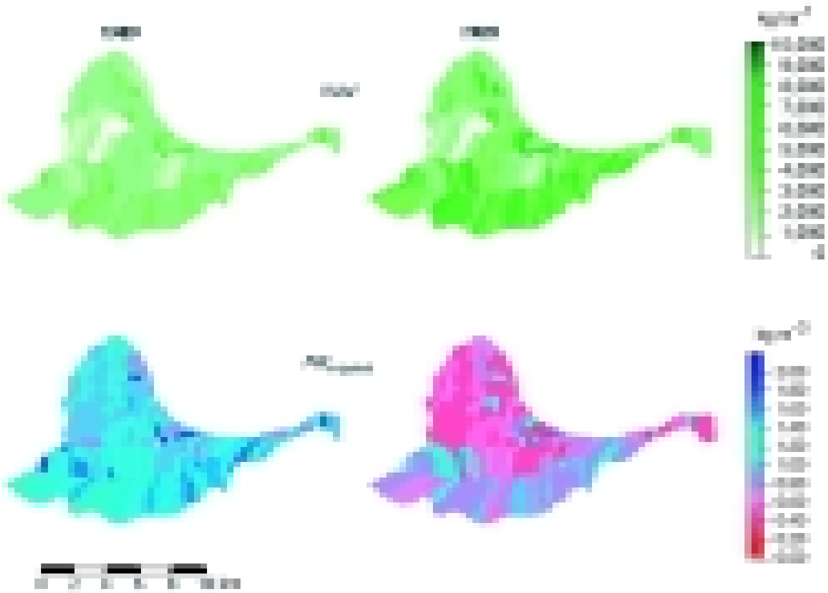
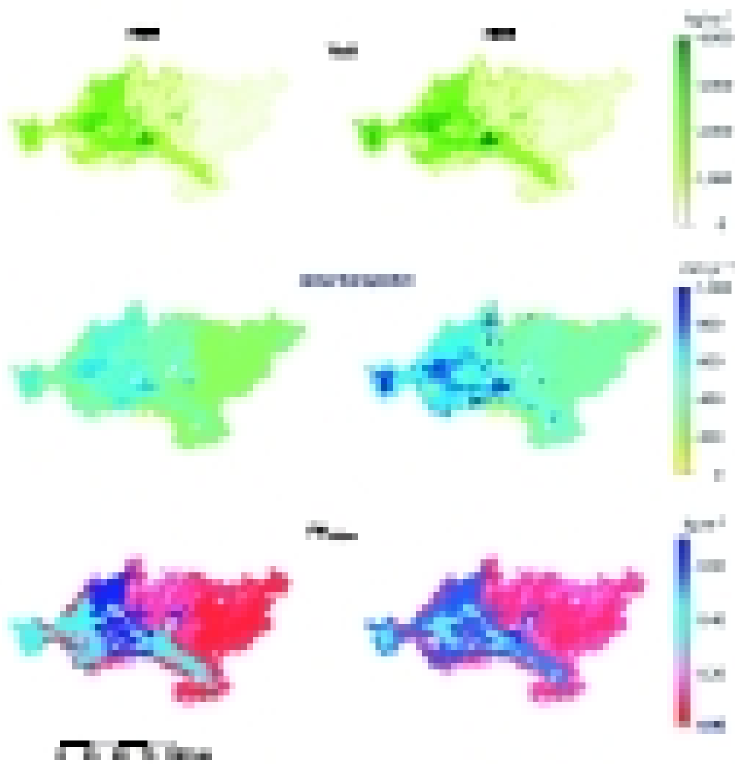


FIGURE 18.
Yield, actual transpiration, and PW_{inflow} for the whole Gediz basin for a dry year (1989) and a wet year (1995).



upstream perform better than those downstream. The areal averages of PW_{inflow} for the 2 years are comparable, 0.18 kg m^{-3} and 0.14 kg m^{-3} for 1989 and 1995, respectively. However, a large variation within the basin exists, with lower values for the nonagricultural areas and higher values for irrigated and nonirrigated land covers. Values for nonirrigated areas are higher than for the irrigated areas, as yields are reasonably high while inflows are limited.

Conclusions

By combining different models, the Gediz basin study has successfully applied and developed new tools that can evaluate irrigation at a variety of scales—at the field level, at the irrigation scheme level, and at the basin scale. Each model uses common datasets and the information obtained can be transferred from one scale to another.

At the crop scale, the SWAP model can relate the quantity, quality, and timing of irrigation water to crop production. At the scale of the individual irrigation scheme, an integrated SWAP model can take account of factors such as crop choice, amount and timing of irrigation supply, source of irrigation water (surface water or groundwater), and alternative delivery mechanisms. Further, the model is able to incorporate the information on performance derived from the crop-scale model with the water supply information provided by the basin-scale SLURP model.

The basin-scale hydrological model is able to bring together the basic data on the irrigation schemes, set it in a broader basin context, and include information on the climate and river flows. The basin-scale model can then be used to investigate the hydrologic and hydraulic effects of different water uses within the basin. Apart from the climatic and streamflow data, all the information necessary for the hydrological model was freely obtained from public-domain databases on the Internet.

During the Gediz study, the combined models have proved the ability to investigate the effects of alternative crops, alternative management practices, and alternative water supply scenarios. The use of these models enabled a more complete investigation of the true performance of irrigation schemes under various water management and water availability options. The results of the models could be used to test and apply new methods to increase the productivity of water through better management of irrigation and water-basin systems.

Literature Cited

Doorenbos, J.; and A. H. Kassam. 1979. *Yield response to water.* FAO Irrigation and Drainage Paper 33. Rome, Italy: FAO.

Droogers, P.; and G. Kite. 1999. Water productivity from integrated basin modeling. *Irrigation and Drainage Systems* 13:275–290.

Droogers, P.; and G. W. Kite. 2000. Remotely sensed data used for modeling at different hydrological scales. *Hydrological Processes*.

Droogers, P.; W. G. M. Bastiaanssen; M. Beyazgül; Y. Kayam; G. W. Kite; and H. Murray-Rust. 1999. Agro-hydrological analyses of an irrigation system in Western Turkey using simulation modeling. *Agricultural Water Management* (in press).

Droogers, P.; G. W. Kite; and W. Bastiaanssen. 1998. Land cover classification using public domain datasets: Example for Gediz Basin, Turkey. In *Proceedings of International Symposium on Arid Region Soils,* 34-40. Menemen, Turkey, 21–25 September 1998.

Eastman, J. R. 1997. *Idrisi for Windows user's guide, version 2.0.* Massachusetts, USA: Clark University for Worcester.

Feddes, R. A.; P. J. Kowalik; and H. Zaradny. 1978. *Simulation of field water use and crop yield.* Simulation monographs. Wageningen, the Netherlands: Pudoc.

Garbrecht, J.; and J. Campbell. 1997. *TOPAZ Version 1.20, an automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization, user manual. Rep.# GRL 97-4.* Grazinglands Research Laboratory, Agricultural Research Service. El Reno, Oklahoma: United States Department of Agriculture.

Granger, R. J. 1995. A feedback approach for the estimation of evapotranspiration using remotely sensed data. In *Applications of remote sensing in hydrology, Proceedings of the Second International Workshop, 18–20 October, 1994,* ed. G.W. Kite, A. Pietroniro and T. Pultz, 211–222: Symposium No. 14. Saskatoon, Saskatchewan: National Hydrological Research Institute.

Kite, G. W. 1997. *Manual for the SLURP hydrological model.* Saskatoon, Canada: National Hydrological Research Institute.

Kite, G. W.; and P. Droogers. 2000. Comparing evapotranspiration estimates from satellites, hydrological models and field data. *J. of Hydrology* 229:3–18.

Kite, G. W.; A. Dalton; and K. Dion. 1994. Simulation of streamflow in a macro-scale watershed using GCM data. *Water Resources Research* 30(5):1,546–1,559.

Lacroix, M.; and L. W. Martz. 1997. Integration of the TOPAZ landscape analysis and the SLURP hydrologic models. *Proc. Scientific Meeting, Canadian Geophysical Union*, p.208. Banff, Alberta: University of Calgary.

Molden, D. 1997. *Accounting for water use and productivity.* SWIM Paper 1. Colombo, Sri Lanka: International Irrigation Management Institute.

Molden, D.; R. Sakthivadivel; C. J. Perry; C. de Fraiture; and W. H. Kloezen. 1998. *Indicators for comparing performance indicators of irrigated agricultural systems.* Research Report 20. Colombo, Sri Lanka: International Water Management Institute

Morton, F. I.; F. Ricard; and S. Fogarasi. 1985. *Operational estimates of areal evapotranspiration and lake evaporation - Program WREVAP.* NHRI Paper 24. Ottawa: National Hydrological Research Institute.

Slough, K; and G. W. Kite. 1992. Remote sensing estimates of snow water equivalent for hydrologic modelling. *Canadian Water Resources Journal* 17(4):323–330.

Spittlehouse, D.L. 1989. Estimating evapotranspiration from land surfaces in British Columbia. In Estimation of Areal Evapotranspiration, *IAHS* 177:245–253.

Su, M.; W. J. Stolte; and G. van der Kamp. 1997. Modelling wetland hydrology using SLURP. *Proc. Scientific Meeting of the Canadian Geophysical Union*, p. 198. Banff, Alberta: University of Calgary.

Tietje, O.; and M. Tapkenhinrichs. 1993. Evaluation of pedo-transfer functions. *Soil Sci. Soc. Am. J.* 57:1,088–1,095.

Van Dam, J. C.; J. Huygen; J. G. Wesseling; R. A. Feddes; P. Kabat; P. E. V. VanWalsum; P. Groenendijk; and C. A. van Diepen. 1997. *Theory of SWAP version 2.0.* Technical Document 45. Netherlands: Wageningen Agricultural University and DLO Winand Staring Centre.

Van Diepen, C.A.; J. Wolf; H. Van Keulen; and C. Rappoldt. 1989. WOFOST: A simulation model of crop production. *Soil Use and Management* 5:16–25.

Internet References

[1] USGS GTOPO30: http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html

[2] USGS land cover: http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html

Research Reports

30. *Mechanically Reclaiming Abandoned Saline Soils: A Numerical Evaluation.* S. A. Prathapar and Asad S. Qureshi, 1999.

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ISSN 1026-0862
ISBN 92-9090-411-9